THERMAL AND ENERGY EFFICIENCY SOLUTIONS FOR NATURAL GAS COMPRESSION USING INDUSTRIAL AUTOMATION

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The paper presents as results a proportional–integral–derivative (PID) function developed for a programmable logic controller (PLC) used to protect a screw electro-compressor from its thermal energy and a complex PLC algorithm developed for ensuring energy efficiency. The operating mode of an electro-compressor can be imposed as manual mode or automatic mode, and can be selected from a developed HMI screen. The algorithm behind both manual mode and automatic mode will be analyzed in the article. The efficiency of energy consumption will result from the variation analysis of the current consumed by the main electric motor that drives the compression unit. The oil temperature evolution will also be analyzed from the parameter records, which is kept under control from a thermal point of view by a custom parameterized PID function. It will be detailed in the article how this custom parameterization of the PID function was performed and what the implications are from the point of view of the thermal efficiency for the electro-compressor.

1. INTRODUCTION

Traditional screw compressors operate at a constant speed, which can lead to energy wastage when full capacity is not required. The motor may continue running at full speed even when compressed gas demand is low.[1]

Fig. 1 – Screw electro-compressor skid.

By using variable speed drives (VSDs), the motor speed can be adjusted dynamically based on real-time demand, reducing power consumption. A VSD enables the motor to slow down or stop when gas demand decreases, preventing unnecessary energy usage [2].

The energy efficiency of screw compressors is analyzed by examining key design parameters, operational conditions, and performance optimization strategies. Therefore, research activities performed in this field highlight factors such as rotor profiles, leakage losses, and variable speed drives, which significantly impact energy consumption [3–5]. Design improvements, operational adjustments, and advanced control techniques are key factors for obtaining the overall energy consumption of a screw electro-compressor [6,7].

Experimental and simulation results demonstrate efficiency improvements through advanced cooling techniques and optimized compressor designs. These findings emphasize the importance of energy-efficient screw compressors in industrial applications and suggest further research into advanced materials and control systems for enhanced performance [3,6].

Energy efficiency in an industrial screw compressor is a critical concept, as it directly impacts operating costs and the environmental footprint of industrial facilities.

The article aims to pursue three objectives, each representing contributions of this article in the field of screw electro-compressor automation.

The first objective of the article is represented by the development of an optimized grid diagram that is applicable to any application of this type, through which the energy efficiency of the screw electro-compressor is ensured.

The second objective is to present an algorithm implemented in the PLC software that ensures energy efficiency of the screw electro-compressor during operation using the optimized grid diagram architecture described in the article. The second objective also aims to demonstrate energy efficiency through 2 case studies obtained using a parameter-measuring method developed in the article.

The third objective defines a PID function with tuning parameters obtained during experimentation of a screw electro-compressor for an Emerson PLC that ensures oil cooling to achieve thermal efficiency.

1. GRID DESIGN AND OPTIMIZATION

The initial version of the electrical grid configuration that was used assumed the use of a soft starter which operates the main engine speed only at its nominal value. Also, it limits the current and reduces mechanical stress when starting the main electric motor that drives the screw electro-compressor.

As it can be seen on Fig.2, the main electric motor is powered by a three-phase 500V power supply from an electrical station and reaches a soft starter that assists in starting the electric motor. The electric motor is started from an operator panel that, by pressing a dedicated button, commands the soft starter and starts the electro-compressor.
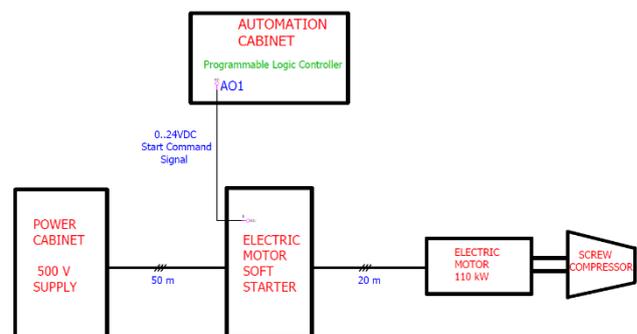

Fig. 2 – Initial grid diagram of the screw electro-compressor.

The optimized version of the electrical network

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configuration presented in Fig. 3 assumed the use of a variable speed drive, which controls the speed and the torque of the electric motor that drives the screw electro-compressor by adjusting the supply frequency and voltage.

The power supply of the main electric motor is a three-phase 500V connected to an electrical station and reaches a variable speed drive which provides a three-phase PWM output voltage to the electric motor that drives the electro-compressor.

Thus, when the electro-compressor is started from the operator panel of the automation cabinet, the electric motor driving the electro-compressor will be controlled in speed through the variable speed drive by the related software algorithm in the PLC of the automation cabinet. The parameters taken from the variable speed drive, such as the current and the speed of the main motor, will be read on the operator panel.
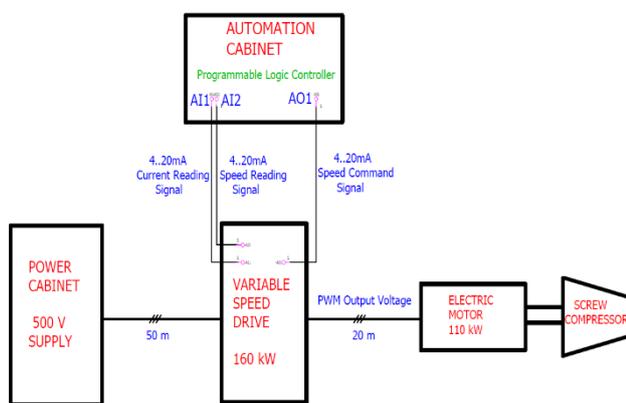

Fig. 3 – Optimized grid diagram of the screw electro-compressor.

3. ENERGY EFFICIENCY ALGORITHM

The operating mode of an electro-compressor can be imposed as manual mode or automatic mode. Both operating algorithms are implemented through PLC software programming.

Operating mode can be selected by an operator from a software-developed HMI screen.

Manual mode involves the user setting an operating speed for the electric motor that drives the electro-compressor.

The input speed range available to the operator is usually between two-thirds of the nominal speed as the lower limit and the nominal speed as the upper limit.
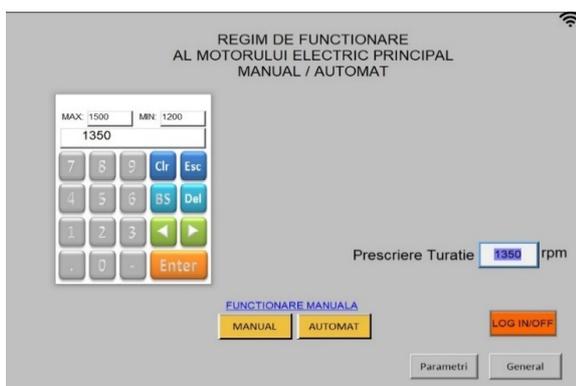
$$N = N_{OP}. \tag{1}$$

Fig. 4 – Electro-compressor operator panel interface for manual mode.

Thus, in Fig. 4, the operator enters the speed value N = 1350 rpm, and once inserted, the electro-compressor motor will operate at a constant speed of 1350 rpm.

Automatic mode has a custom-developed control loop algorithm presented in (2), (3), and (4).

$$P_S < P\_INF => N = 62.5\% x N_S, \tag{2}$$

$$P_S > P\_SUP => N = N_S, \tag{3}$$

$$P\_INF < P_S < P\_SUP =>$$

$$N = \frac{P_S - P\_INF}{P\_SUP - P\_INF} x 37.5\% x N_s + 62.5\% x N_S, \tag{4}$$

where P_s – suction pressure, P_INF – lower suction pressure threshold, P_SUP - upper suction pressure threshold, N – motor speed, N_s – nominal motor speed.

The algorithm involves setting a lower suction pressure threshold (P_INF) and an upper suction pressure threshold (P_SUP).

After the operator enters the two values for the two thresholds, he will finally press the button to insert these values into the algorithm.

Thus, in Fig. 5, the operator enters the threshold values P_INF and P_SUP to establish the automatic adjustment loop of the main motor speed depending on the real-time suction pressure value.
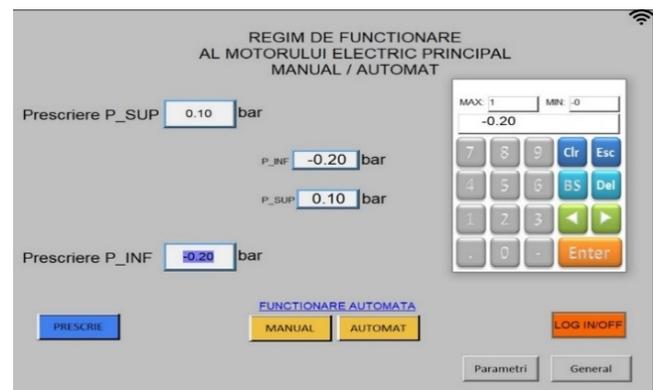

Fig. 5 – Electro-compressor operator panel interface for automatic mode.

Depending on the evolution in time of the suction pressure and the configuration of these two thresholds, the speed of the main electric motor adjusted by the variable speed drive is controlled by the PLC algorithm presented in the article.

4. THERMAL EFFICIENCY METHODOLOGY

The thermal efficiency obtained by implementing industrial automation software solutions in the case of a screw electro-compressor is performed on the oil circuit.

The oil circuit is usually composed of a pump, an oil circuit closing/opening valve, an oil cooler, and a bypass/oil cooler valve.

Due to friction in the compression unit, the oil used for lubrication heats up. To protect the electro-compressor from the thermal energy thus produced, a cooler driven by an electric motor ensures thermal efficiency.

The oil temperature variation is kept under control from a thermal point of view by a PLC software parameterized PID function that drives the cooler motor speed [8].

Therefore, the cooler motor speed will keep the oil temperature T_{oil} under control between 40°C - 50°C.

The parameterization of the Proportional–Integral–Derivative function performed in an Emerson Versamax PLC programming environment is as follows:

$$DeadBand_{upper} = 100, \tag{5}$$

$$DeadBand_{lower} = -100, \tag{6}$$

$$Error_{term} = PV - SP, \tag{7}$$

$$Derivative_{action} = PV, \tag{8}$$

$$Output_{polarity} = POS, \tag{9}$$

The Proportional–Integral–Derivative tunning parameters are declared as follows:

$$Proportional = 6\% \tag{10}$$

$$Integral = 0.6 \text{ rep/sec} \tag{11}$$

$$Derivative = 0 \text{ sec.} \tag{12}$$

In the Emerson Versamax PLC programming environment, parameters are entered appropriately in each box, as shown in Fig. 6.
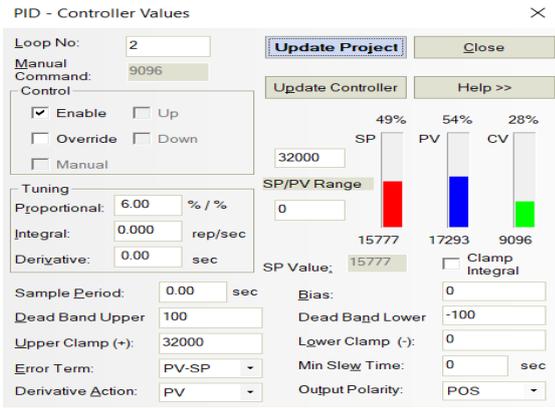

Fig. 6 – Proportional–Integral–Derivative parameters input box of an Emerson Versamax PLC programming environment.

5. ENERGY EFFICIENCY RESULTS

The experimental data was obtained by collecting it by the PLC from the electro-compressor field sensors and transmitting the values of each parameter in the form of an address to the operator panel via the Emerson Ethernet communication protocol.

The operator panel was programmed to record the values of all parameters taken from the PLC on a data flash drive. The programming was performed so that the panel would record the values of each parameter once every 15 seconds. For each parameter, the panel creates an individual data file per day in which the parameter values recorded on that day are found.

The data measurement method is original and is presented in Fig. 7. Accordingly, Case 1 and Case 2 measurements were performed. The load of the compressor is the discharge pressure and influences the current consumed by the electric motor that drives the electro-compressor. The energy efficiency results from this proportional relationship, but also

from the variation of the speed of the electric motor depending on the suction pressure, according to the control loop algorithm (2), (3), (4) implemented in the automation system.
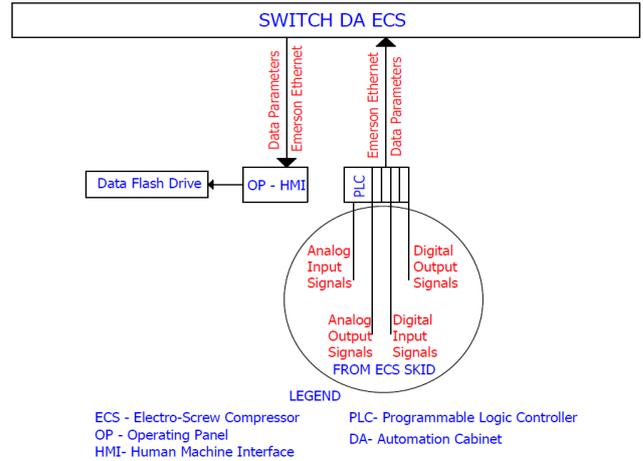

Fig. 7 – Data measurement method

The control loop algorithm has implemented a procedure to automatically stop the electro-compressor if the gas pressure on the suction falls below a certain value and to automatically start the electro-compressor if the gas pressure exceeds a certain value once it has stopped automatically, which substantiates the energy efficiency results.

Data taken from the parameter records of an electro-compressor will be interpreted. Therefore, the efficiency of energy consumption will result from the variation analysis in time of the current consumed by the main electric motor that drives the compression unit, the discharge pressure Pgrs. the motor speed and the suction pressure Pga, as shown in Fig. 8.

(a)
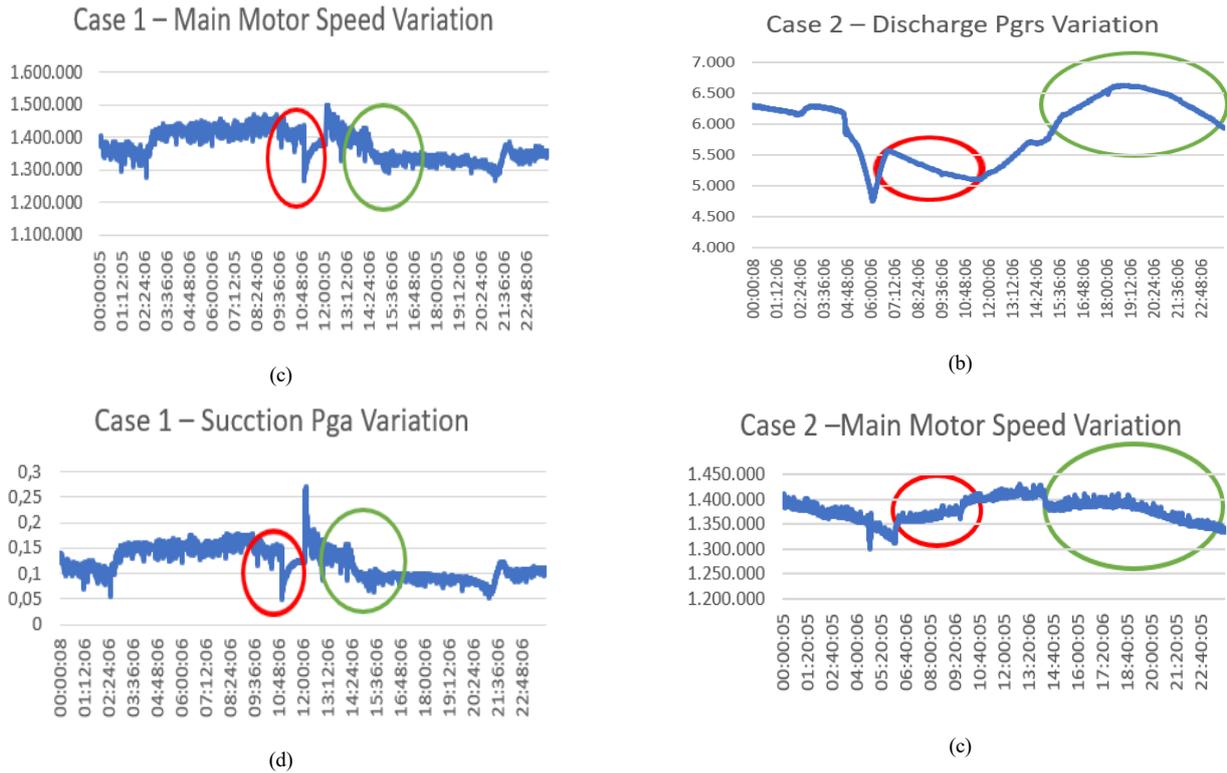

(b)

(c)

(b)

(d)

(c)
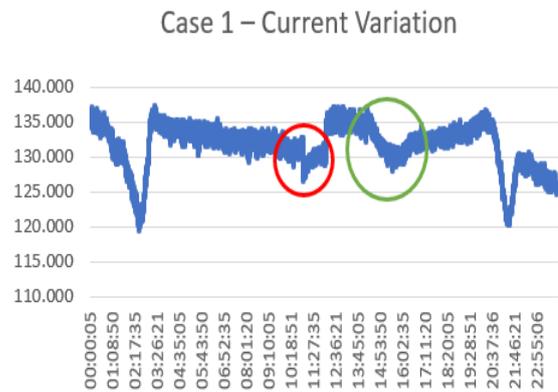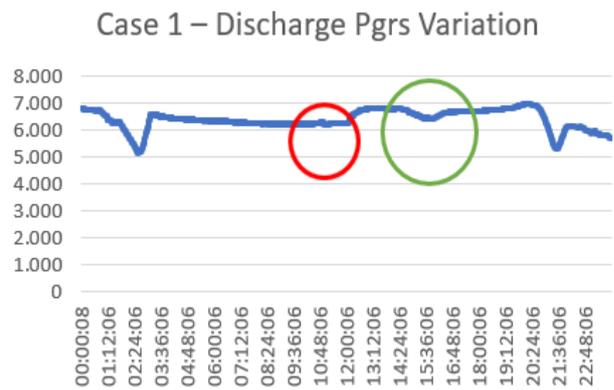
Fig. 8 – Case 1 of energy efficiency of an electro-compressor using industrial automation: (a) variation analysis of the current consumed by the main electric motor; (b) variation analysis of the discharge pressure; (c) variation analysis of the motor speed; (d) variation analysis of the suction pressure.

In case 1, it can be observed in Fig. 8 that, first, for the red circle, the motor current (Fig. 8a) has a decrease in its value, although the electro-compressor load (Fig. 8b) has a constant value. The decrease of the motor current value occurs due to the decrease of the suction pressure value (Fig. 8d) and, through the implemented algorithm, due to the speed decrease of the electric motor (Fig. 8c) that drives the electro-compressor.

This behavior demonstrates the energy efficiency obtained through the control loop algorithm implemented in the automation system

Secondly, on Fig. 8, the green circle again highlights a decrease of the motor current (Fig. 8a), which is due to a small extent to a slight decrease in the electro-compressor load (Fig. 8b), but to a greater extent also to the decrease of the suction gas pressure (Fig. 8d) that, through the algorithm, commands the decrease of the motor speed that drives the electro-compressor (Fig. 8c).

Again, we can observe the energy efficiency obtained through the control loop algorithm.
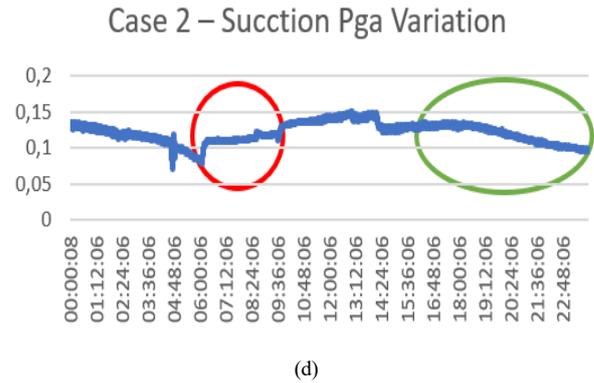

(a)

(d)

Fig. 9 – Case 2 of energy efficiency of an electro-compressor using industrial automation: (a) variation analysis of the current consumed by the main electric motor; (b) variation analysis of the discharge pressure; (c) variation analysis of the motor speed; (d) variation analysis of the suction pressure.

In case 2, analyzing the behavior of the electro-compressor highlighted in Fig. 9 with the red circle, it can be observed that although its load (Fig. 9b) decreases sharply, the variation of the main motor current (Fig. 9a) does not decrease as much as the load because the suction gas pressure (Fig. 9d) increases at that moment, and with it, the algorithm increases the speed of the main motor (Fig. 9c).

Thus, this example can show the dependence of the current consumed both on the electro-compressor load and on the control loop algorithm implemented in the PLC.

The energy efficiency emerges in case 2 from the example highlighted in Fig. 9 by the green circle, which shows a steep increase in the load (Fig. 9b) that determines a slight increase in the motor current (Fig. 9a). The current has a slight, not a steep, increase because it is also influenced by the effect of the control loop algorithm to decrease the speed of the main motor (Fig. 9c) due to the decrease in the suction gas pressure (Fig. 9d).

6. THERMAL EFFICIENCY RESULTS

First, the evolution of the oil temperature over time when

the screw electro-compressor is started is analyzed. At electro-compressor start-up, in Fig.10, the oil temperature, which tends to reach a constant regime, is shown with the red circle. The oil temperature reaches 50ºC in Fig. 10 at the green circle, and cold oil from inside the cooler enters the oil circuit. The oil temperature will decrease when cold oil mixes with the 50ºC oil, as seen in Fig.10 with the purple circle.

Eventually, all the oil inside the oil circuit will start to heat up again, and the PID function implemented into the PLC software will manage to achieve thermal efficiency by stabilizing the oil temperature around the value of 45ºC with the cooler, as seen in Fig.10 with the yellow circle.
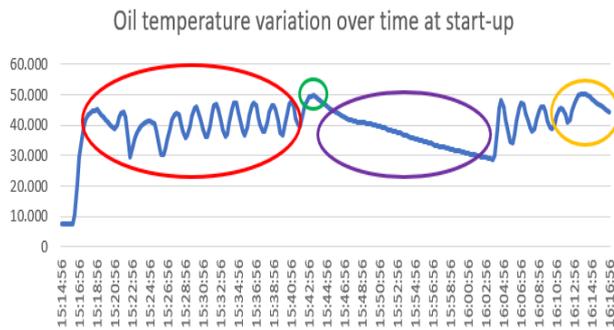

Fig. 10 – Oil temperature variation over time at electro-compressor start-up.

An analysis is carried out on the evolution over time of the oil temperature in the continuous operation of an electro-compressor over 24 hours.

During the night, as seen in Fig. 11 with the yellow circle, the outside temperature is colder than during the day, as seen on Fig. 11 with the green circle. This aspect is reflected in the oil cooling process.

During daytime or nighttime electro-compressor normal operation, oil temperature T_{oil} is kept between 40ºC - 50ºC by the PID software function, resulting in thermal efficiency.
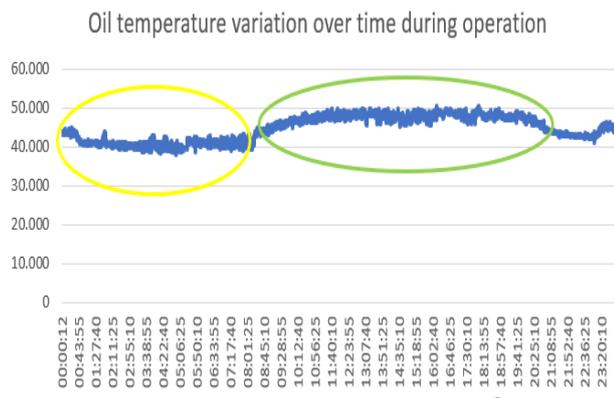

Fig. 11 – Oil temperature variation over time on electro-compressor normal operation.

7. CONCLUSIONS

Thermal efficiency in a screw electro-compressor is about optimizing its operation through advanced technologies like PLC software methodology implemented on a VSD that runs an oil cooler motor or a gas cooler motor. It is recommended a proper system design, regular maintenance and ensuring that the electro-compressor runs in a way that minimizes wasted energy.

A screw electro-compressor was designed to automatically shut down and start up based on gas pressure availability to prevent equipment wear and thus providing this equipment with high energy efficiency. This objective was achieved using industrial automation through an energy efficiency algorithm.

This approach differs from existing literature from a conceptual point of view, considering the implementation of the entire algorithm was performed by using a single programming language, namely Ladder. No scripts or multiple programming languages are used. To implement the algorithm, a single senior programmer who knows only the Ladder programming language is required, which implies speed and efficiency in the implementation of such an automation project.

Experimental data in the article show that implementing a PLC energy efficiency algorithm reduces power consumption significantly over time, especially in applications with fluctuating load requirements. This contributes to lower operational costs and improved overall system efficiency.

The automation solutions described in the article can also be integrated into other applications, such as a wastewater treatment blower or a centrifugal compressor. Depending on the application, adjustments can be made to the PLC control strategy to optimize the installation's operation.

A limitation of this automation solution is for a piston compressor application. Usually, these applications operate without being equipped with a VSD, therefore without the possibility of having an algorithm based on the speed variation of the main motor. However, even for these applications, part of the energy efficiency algorithm can be applied, namely the compressor automatic start and stop, depending on a working parameter, which can be a gas suction pressure.

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